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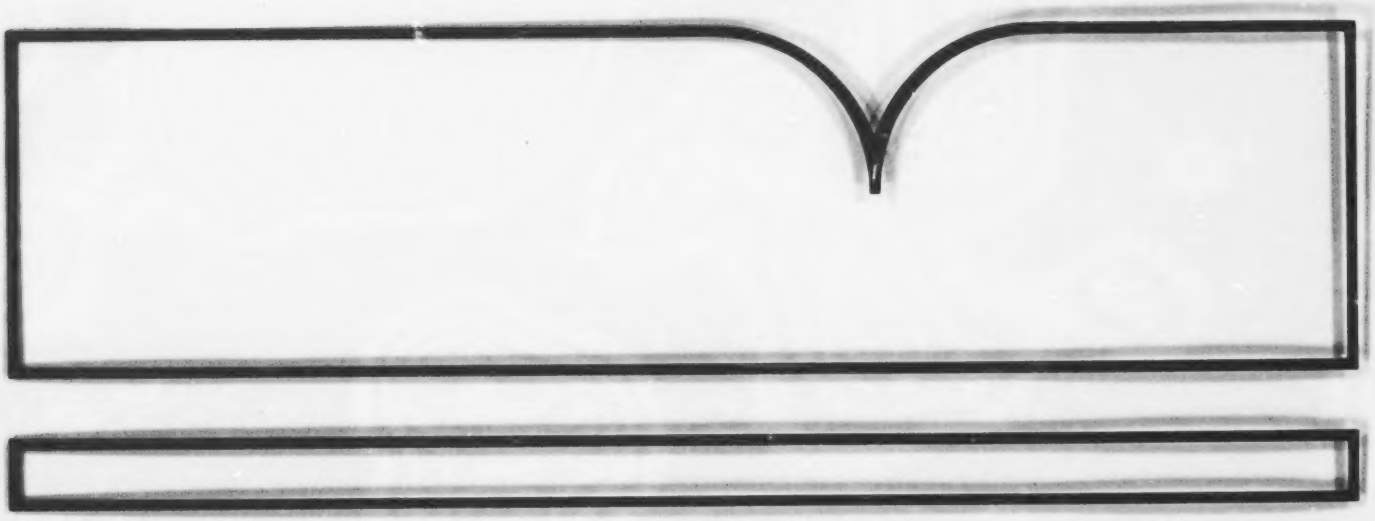

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16. ABSTRACT

In a wind-tunnel study, recorded video images of the top view of smoke dispersion in the wake of a building were analyzed. A continuous source of smoke was emitted at floor level, midway along the leeward side of the building. The technique and usefulness of analyzing video images of smoke is demonstrated in a study of building effects on smoke dispersion.

The presentation discusses how the video image intensity is corrected for background intensity and then normalized to a scale of 0 to 100 percent. Profiles of the normalized image mean intensity are compared with similar profiles for the mean concentration of hydrocarbon tracer. The distributions of intensity of cross-stream profiles are discussed. These distributions were analyzed in time and space. Also, time-averaged cross-stream profiles of mean, standard deviation, and other statistics of image intensity are compared with traditional concentration measurements for symmetric wake flow.

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VIDEO IMAGE ANALYSES OF THE CROSS-STREAM DISTRIBUTION OF SMOKE IN THE NEAR WAKE OF A BUILDING

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1. INTRODUCTION

Investigations of the distribution of pollution in the near-wake region of buildings are needed to understand better the complicated dispersion processes caused by the disturbed air motions near buildings. Concentrations of pollution as emitted into the ambient air are often potentially hazardous. The dilution of these emissions with the surrounding air naturally reduces the pollution concentrations. The aerodynamic wake flow and thus pollution concentrations are highly dependent on the building shape and length scales, and the approach boundary layer flow. The lateral and vertical mixing initially spread the pollution over the width and the height of the building, respectively. The pollution concentration is also influenced by the downstream extent and the residence time of the recirculating flow adjacent to the building (see e.g., Vincent [1978] and Fackrell [1984]).

For a continuous source of pollution in the near-wake region, the spatial distribution of average concentration represents the superposition of a series of instantaneous distributions characterizing the mixing process. The variation within the series reflects the transient nature of building-induced vortex-shedding and the interaction of the building wake flow with the boundary layer flow. In the field, variation in the wind direction, wind speed, and atmospheric stability can also significantly influence the overall distribution.

The measurement of fluctuating concentrations in the wake of buildings has been somewhat limited by the adequacy of the instrumentation. Wind-tunnel modeling is a very practical method for evaluating building-wake influences. However, the reduced scaling for wind-tunnel models requires the use of analyzers having a faster response time than is required for field measurement. Li and Meroney [1983] used the technique of Wilson and Netterville [1983] in a wind-tunnel study to evaluate the fluctuation in concentration downwind of a cubical building. The centerline plume fluctuations (standard deviation of the concentrations) were found to range from 1 to 3 times the mean concentration within one building height downstream of sources on the building. The centerline plume fluctuations beyond three building heights downstream were found to be approximately 0.35 times the mean concentration. The fluctuations at similar distances downstream of a source in a boundary layer not affected by any wake flow range from 1 to 2 times the mean concentration [Wilson et al., 1985]. The lower fluctuation intensities in the wake of the building are a result of the more rapid and thorough mixing throughout the wake flow.

In this study, we investigated the cross-stream distribution of smoke in the near wake of a model building. Video images of the smoke were digitized and analyzed. These analyses of video images of smoke provide details on the temporal and spatial scales, which can provide a better understanding of the dispersion processes than is possible from traditional point-sampling techniques. The purpose of our study is to evaluate the cross-stream distribution for a series of video images to demonstrate the application of video image analyses. These analyses are a continuation from Huber and Arya [1985]

2. EXPERIMENT TECHNIQUES

The experiment was conducted in the U.S. Environmental Protection Agency's Meteorological Wind Tunnel [Snyder, 1979]. The building height (H) was 0.2 m. The along-stream building length was equal to the building height. The cross-stream building length was twice the building height and was oriented perpendicular to the direction of the free-stream flow. The boundary layer thickness was 5 times the building height. The mean velocity profile was typical of a neutrally stratified boundary-layer flow. The mean velocity, upstream of the building was 2 m/s at an elevation of 0.5H. The building Reynolds number, using this velocity and the building height H as a length scale, was 26,700. An oil-fog smoke was generated and emitted into the wind tunnel through a pipe, with the outflow pointed downstream. The stream of smoke simulated point-source emissions at floor level, midway along the leeward side of the building.

* On assignment from the National Oceanic and Atmospheric Administration, U. S. Department of Commerce.

Black-and-white video images of smoke were recorded at a rate of 30 pictures per second with a camera connected to a standard VHS recorder. The camera was mounted outside the wind tunnel, 2.5 m above the floor, looking down through a ceiling window. A flood light was placed 3 m downstream from the source. The light was aimed horizontally upstream toward the building. The recorded picture covered a region approximately 1.5 m cross-stream by 1 m downstream from the building. The U.S. National Television System Committee (NTSC) broadcast television signal system was used. The video luminance analog signal was digitized by a video sequence processor at the North Carolina State University's Image Processing Laboratory. The digitized luminance signal from the picture is on a unitless gray scale from 0 to 255. A value of zero would result for zero luminance and a value of 255 would result for full-scale saturation in the luminance signal. However, the video sequence processor has a guard-band protection which was designed to limit the signal extremes. These limited digitized values to fall between 16 and 240 (i.e., between 6 percent and 94 percent of full scale).

The digitized luminance value is referred to here as the video image intensity. In this study, a 15-s time series of rows of digitized pixels, corresponding to the cross-stream profile at a distance x=3H from the source, were analyzed. This distance is just downstream of the recirculating flow near the building. Each pixel among the 450 rows corresponds to a 2.2-mm-square field of view.

3. NORMALIZATION OF INTENSITY

A 15-s series of cross-stream pixel intensities from pictures with smoke was compared with a similar series without smoke. The mean intensity profile without smoke is shown by the long-dash curve (D) in Fig. 1. The lower values along this profile are about 50 for $-3<y/H<2$. A trend of decreasing value is apparent for $y/H>2$. The pixel intensity for the no-smoke series represents light scattered and reflected from the background surroundings in the field of view. The variation across the profile is primarily a measure of the reflectance from the surface. The surface of the tunnel was covered with gravel having variable diameters of less than 10 mm. The gravel was painted a flat black color to minimize its reflectivity, and 10-cm grid of white lines was painted to provide reference mainly over the field of view. The larger peaks in the profile correspond to some of these painted lines. The lines were also observed to show through the pictures with smoke. The data from pictures with smoke were preprocessed to smooth over the lines (i.e., the local peaks were eliminated by linearily interpolating across them). The resulting profiles for the mean, maximum, and minimum intensities for this series are also shown in Fig. 1. For $y/H>2$, these values were observed to be approximately equal to similar values without smoke. This indicates that no smoke diffused to these cross-stream distances. The standard deviation of intensity for pixels in which there was no smoke (for both series) ranged from 3 to 5. The difference between the maximum intensity and the minimum intensity ranged from 15 to 30 for these same pixels.

The profiles with smoke in Fig. 1 show that the diffused smoke from the point source favored one (negative y/H) side. The air flow around the building should be laterally symmetric in the average. The distribution of smoke, however, was observed to be sensitive to even a slight error in the building orientation. Also, since the smoke was emitted with excess momentum, a precise alignment of the jetting smoke was difficult. Both of these factors and possible asymmetry of vortices shed from the sides of the building resulted in the smoke not being diffused equally on both sides of the building. However, the distributions were nearly symmetric for the cross-stream profile near the centerline ($-3< y/H <2$). The minimum intensity profile (line C) is consistent with the uniform background of approximately 50 across the profile. This indicates that at the fixed downstream position being studied here, the illumination from the light was nearly uniform over the cross-stream profile of interest and that there were apparently times when there was little smoke at every lateral pixel.

The value of the image intensity above the background level is related to the integrated smoke particle density through the field of view. With this in mind, the original intensities in the smoke plume were first corrected by subtracting 50 (estimated background intensity) and then normalized to give a range of 0-100 percent. The normalized scale range should correspond to a unitless scale providing an indirect measure of the number of smoke particles up to full-scale saturation.

Figure 2 compares the cross-stream distribution of mean intensity with the lateral distributions of mean hydrocarbon concentration at three elevations after normalizing them by their centerline peak values. Since the image intensity is related to a vertically integrated concentration, its value should be mostly influenced by concentration within the central core of the plume (i.e., $z/H<1.5$). A separate evaluation of several vertical profiles of concentration found that the vertically integrated average concentration in the plume could be well approximated by the point concentration at $z/H=1$ in the central part of the plume. Near the fringes of the plume, concentrations at $z/H=1$ approach zero before concentrations at the ground-level approach zero. The vertically integrated concentration profile also shown in Fig. 2 was derived from the lateral profiles at $z/H=0$, 0.5, 1.0, 1.5, and 2.5.

The similarity between the profiles of hydrocarbon concentration and the normalized smoke intensity supports the belief of a usefulness and accuracy of our video image analysis technique. The cross-stream profile of mean normalized intensity can be used to study the distribution of smoke. The fluctuating intensities can be used to study the evolution of the plume. In the remainder of this paper, the term intensity refers to the normalized image intensity.

4. TEMPORAL-SPATIAL DISTRIBUTION

The distributions of intensity in the 15-s series of cross-stream profiles vere analyzed as functions of coordinates in time and space. Temporal plots of intensity for selected pixels vere examined to provide a more detailed look at the pattern of smoke over temporal-spatial coordinates. The plots for y/H=0.0, -0.5, -1, and -2 presented in Figs. 3a and 3b are representative of the observed pattern. The intensities among pixels within the core of the plume (e.g., y/H=0.0, -0.5) were all highly correlated. Over time, large fluctuations of intensity correspond to the passage of vortices. The pattern of maximum and minimum intensities near the edge of the building (e.g., y/H=-1.0) are comparable but more peaked and slightly out of phase with the central core of the plume. The higher standard deviation of the fluctuating intensity is typical of the fringe of a meandering plume. Farther to the side of the building (e.g., y/H=-2.0) the intensity fluctuations are reduced. This pattern is indicative of being far toward the edge of the plume. Smoke is carried to this region when parcels break away from the central core. These parcels are then additionally diluted by the surrounding clean air.

5. CROSS-STREAM DISTRIBUTION OF TEMPORAL STATISTICS

The cross-stream distributions of several statistics of 15-s time series of intensity are presented in Fig. 4. Peaks in the standard deviation of intensity are found to occur downstream of the sides of the building. Naturally, the standard deviation approaches zero at the outer fringes of the plume where there are only dilute patches of smoke that broke away from the central core. The ratio of the standard deviation to the mean intensity ranged from 0.25 at the center to 0.4 near the edges of the building. These values are comparable with estimates and predictions from previous studies of fluctuating concentrations for point samples near a building. The ratio of the standard deviation to the mean intensity becomes highly variable (indeterminate) near the outer fringe of the plume where both the mean and standard deviation tend toward zero. This is due to the decreasing intermittency (fraction of time that significant smoke was observed) away from the central core of the wake flow. The cross-stream distribution of the skewness and kurtosis of the time series of intensity similarly correspond to the intermittency of smoke. The zero value of skewness near the center indicates a symmetrical distribution over time. The larger skewness away from the center indicates that the distribution becomes increasingly influenced by a few occurrences of relatively large values of the intensity. The deviations in kurtosis from the Gaussian value of 3 ranged from -0.25 to 0.25 across the central core of the plume, indicating again the nearly Gaussian distribution in the core of the plume. The extremely large kurtosis near the fringe of the plume indicates that there are a few large positive deviations in the intensity from the mean at the fringes of the plume. These are also reflections of the vanishingly small values of standard deviation there.

6. CONCLUSIONS

The usefulness of analyzing video pictures of smoke is favorably demonstrated in this paper. The video-image analysis is shown to be a viable quantitative technique for studying building-wake effects on smoke dispersion. The framing rate of 30 pictures per second is found to be adequate for studying the fluctuating intensity. The ratio of the standard deviation to the mean intensity across the building wake was found to range from 0.25 to 0.4 at x/H=3 (just downstream of the cavity region). This is comparable with previous measurements of fluctuating tracer point concentrations in building wakes.

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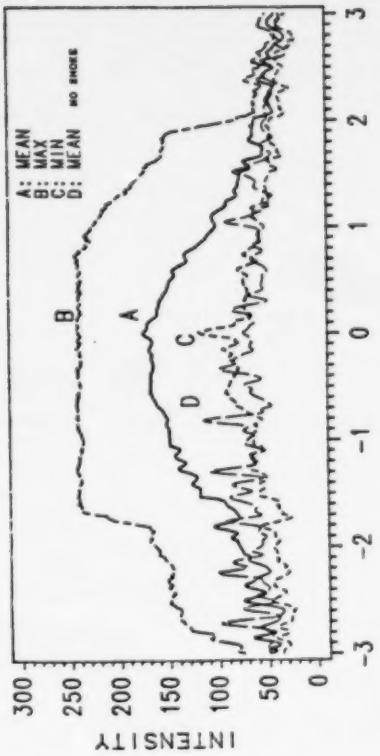

Fig. 1. Cross-stream profiles of video intensity (non-dimensional).

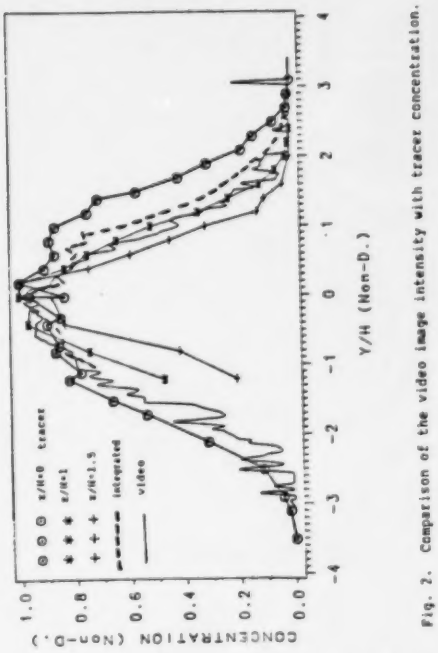

Fig. 2. Comparison of the video image intensity with tracer concentration.

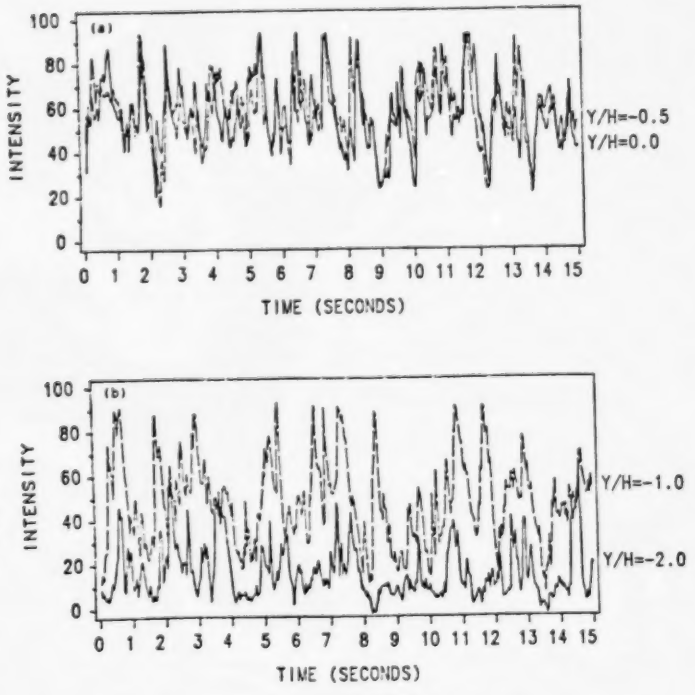

Fig. 3. Temporal variations of video image intensity (percent): (a) at y/H=-0.5, 0, (b) at y/H=-1, -2.

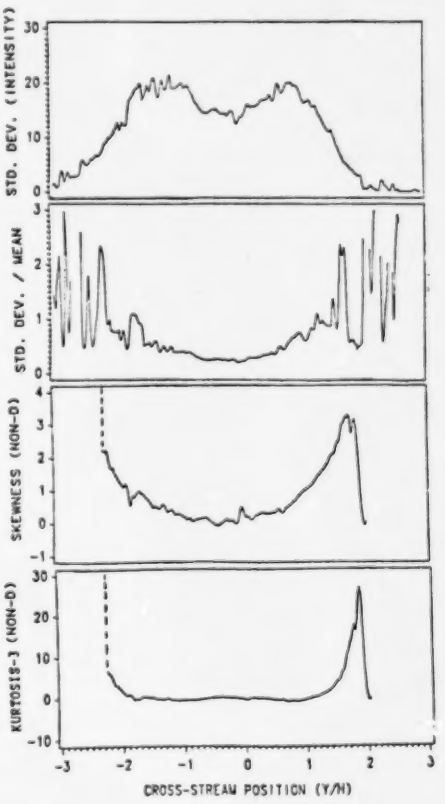

Fig. 4. Cross-stream profiles of temporal statistics.